An Evaluation of Air Force Aircraft Battle Damage Repair Techniques Applicable to Repair Activities Onboard the International Space Station

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Abstract

United States Air Force (USAF) Aircraft Battle Damage Repair (ABDR) strategies, techniques and technologies are directly applicable to NASA efforts to develop on-orbit repair capabilities for the International Space Station (ISS). At the operational level, USAF repair strategies developed since the Vietnam War stress the need for methodical damage assessment, categorization, and repair. This approach should be adopted for future repair operations onboard the ISS. At the technical level, repairs based upon material ultimate properties, preparation for damage to multiple systems and specialized damage effects have shaped ABDR techniques to provide flexible repair strategies for Air Force aircraft. These techniques should also be considered when developing ISS repair strategies. Overall, a baseline for comparison between ISS repair and ABDR clearly demonstrates the need for further technical interchange. Lessons learned from ABDR experiences will provide early insight into techniques and strategies proposed for on-orbit ISS repair operations.

Introduction

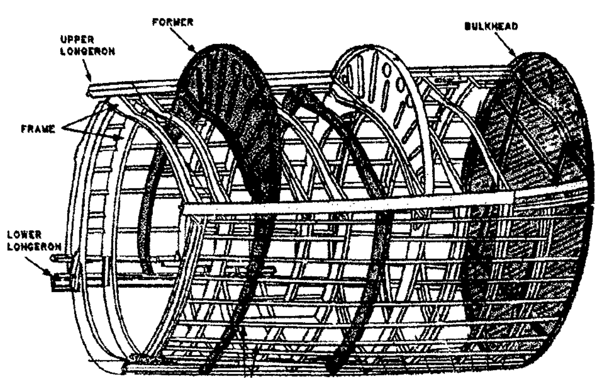
Scientists estimate there are more than 2 million kilograms (4.4 million lbs) of particles in low earth orbit (LEO). These objects, known as orbital debris (OD), vary in size and travel at approximately 9-12 kilometers per second, presenting the threat of collision with orbiting spacecraft. Studies conducted by the Denver Research Institute predict that given a high velocity penetration in the ISS, holes from 1 to 5 inches in diameter can be expected. Coupled with the possibility of micrometeoroids entering earth's orbit (meteor showers such as the Leonids) and with recent damage experiences on the MIR Space Station, the probability that damage repair operations will be required in the projected 10 year life of the ISS is high.

The afore mentioned facts, as well as other studies conducted on micrometeoroid/orbital debris (M/OD) prompted the initiation of a NASA effort aimed at developing temporary and permanent repair technologies for the ISS. Current strategies for repair call for initial leak detection and temporary repair operations, followed by comprehensive repair operations and recertification for habitation by ISS crews. Proposed strategies and techniques are very similar to techniques used by the USAF in Aircraft Battle Damage Repair (ABDR).

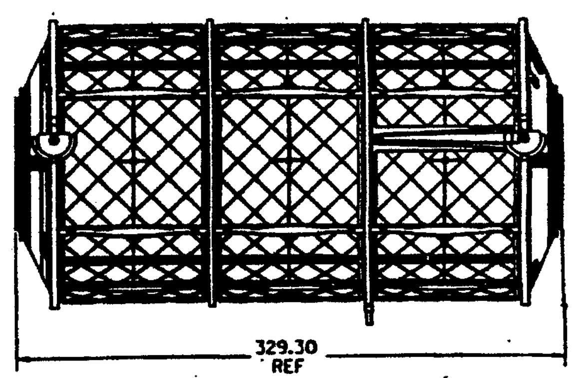
The origin of ABDR can be traced back to many conflicts. In World War II, the Royal Air Force used a variety of repair strategies to ensure damaged aircraft were returned to fighting condition during the Battle of Britain. These repair techniques were crucial to the sustainment of counter-air efforts against the Luftwaffe. In 1965 the USAF developed Rapid Area Maintenance (RAM) for fighter aircraft that sustained combat damage over the skies of Vietnam. Gaining experience in structural repair, the RAM was reorganized in 1967 to form Combat Logistics Support Squadrons (CLSS). After gaining widespread success, rapid repair strategies were developed for nearly every USAF aircraft. Damage repair techniques were also developed by Israel in the 1973 Yom Kippur War. Today, what is now known as ABDR relies on early experiences in aircraft repair strategy, techniques, and technologies. Applying these experiences to ISS repair operations can be accomplished by first examining similarities and differences of these two repair methods.

Material and Damage Similarities: A Basis for Comparison

An important similarity between ABDR and ISS repair strategies is that the primary structures are composed of similar materials. Many aircraft structures utilize aluminum alloys for their high strength to weight ratio, resistance to corrosion, and ease of fabrication. Likewise, most of the ISS modules utilize aluminum alloys for primary structure (U.S., ESA, and NASDA modules are made of Aluminum Alloy 2219-T87, while the RSA uses its own alloy, AMG6). ISS lab materials are closely related to 2024 alloys used in clad form for many aircraft structures. Both display excellent resistance to corrosion and creep, and perform well at extreme temperatures. Material similarities provide an excellent baseline for comparison between ABDR and ISS repair techniques. A visual comparison is provided to the reader in Figure 1.



Aircraft Fuselage



U.S. Lab Module

Figure 1. A comparison of a typical aircraft fuselage structure and the U.S. Lab Module

Examining systems present on aircraft and the ISS leads us to additional similarities. Both structures contain numerous pressure vessels, with uses ranging from human habitation to fluid storage (fuel tanks, liquid oxygen tanks, batteries, etc.). Further, utility runs in the form of high-pressure gas lines, power supply, avionics, are used on both the ISS and modern aircraft. This fact provides yet another baseline justification for validating a comparison between ISS and aircraft structures. As an example, a photograph depicting various systems external to the Unity Module is provided in Figure 2.

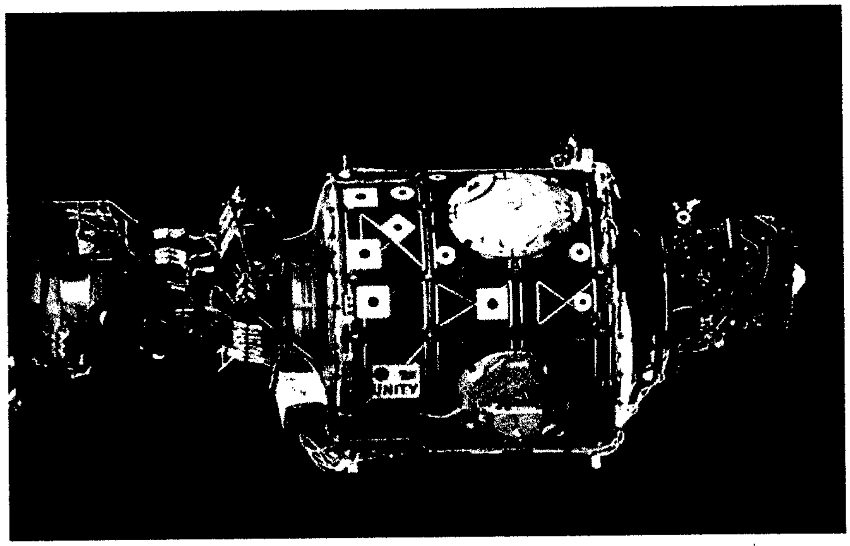
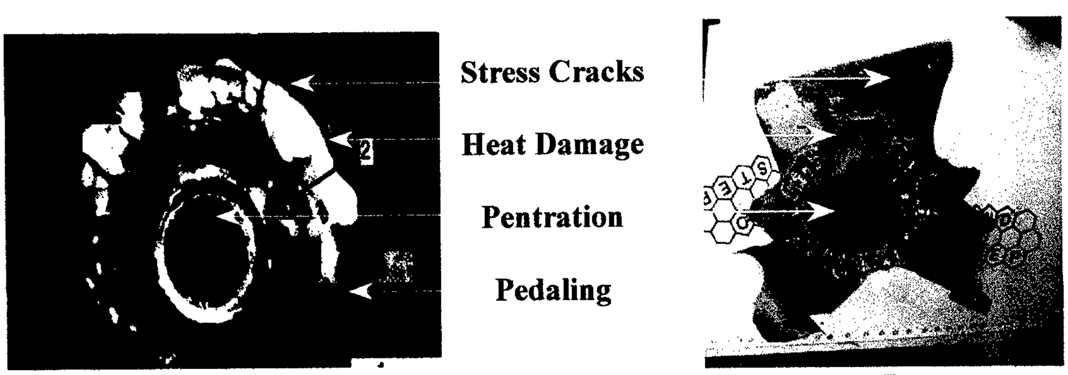


Figure 2. Critical systems external to the ISS (courtesy NASA Public Affairs)

Given similar materials and high velocity particle impacts (M/OD for ISS modules and Anti-Aircraft Artillery, or AAA, for aircraft), similarity in damage provides further rational for comparing ISS and aircraft damage repair strategies. Although aircraft AAA velocities are, on the average, slower than projected ISS impacts (M/OD velocity is 3-12 km/s, while modern AAA velocities average 1-2 km/s) observed damages were similar in nature. Hypervelocity impact tests on spacecraft structures, as well as documented aircraft AAA damage recorded the appearance of a primary penetration hole, with effects due to stress cracks, non-uniform "pedaling," heat damage, and dynamic responses. Figure 3 depicts the similarity in damage between an OD impact on NASA's Long Duration Exposure Facility (LDEF), and an explosive impact test conducted on an F-15 wing.



A
LDEF Penetration Hole
Approximately ¾" Wide

B
F-15 Wing Impact Simulation
Approximately 20" Wide

Figure 3. Comparison between LDEF penetration and F-15 impact simulation

Although both impacts differ considerably in size, stress cracks, heat damage, pedaling, and a well defined penetration hole were common to both impacts. Heuristic analysis of materials, systems, and damages demonstrates that an adequate similarity exists between the two fields to justify application of ABDR lessons to ISS repair operations.

Operational Lessons Applicable to ISS Repair

ABDR repair strategies developed during the Vietnam War stress methodical damage assessment, categorization, and repair processes. Prior to Vietnam, individual aircraft damage repairs were developed individually. This process often slowed down the rate at which individual repairs could be accomplished. As certain types of damages became more and more common, so did the manner in which they were repaired. Standard Technical Orders (T.O.) were developed for aircraft structural, electrical, and mechanical repairs. These "general" T.O.s were soon followed by aircraft specific T.O.s, which included detailed drawings that allowed technicians to assess, classify and repair virtually any damage on the aircraft. This technique increased the speed of repair, since CLLS airmen could quickly refer to the T.O. and find the damaged part, it's function, and recommended repair. Each structure was also arranged in various categories (one-through five), so airmen could determine whether or not the structure was non-essential, critical for mission effectiveness (load bearing), or critical for safety. In addition to classes of structure, damages were separated into various classes in order to determine courses of action give a certain size of damage.

In determining a flexible way to conduct ISS repairs, development of a general repair T.O., including categorization of substructures and classification of damage is recommended. Structure categories, shown in Figure 4, will guide repair teams toward developing a hierarchy of repair priorities onboard the ISS. Establishment of damage classes (Figure 5) will provide efficient insight into whether or not a give size of damage can be repaired for a given structure.

Structure Categories	Definition
I	Carry primary loads/essential for structural integrity
II	Structure transfers loads to primary structural members
III	Non-essential structure/does not insure structural integrity
IV	Installed for other then structural purposes
V	Not feasible for repair

Figure 4 Proposed ISS structural categories

Class	Definition
A	Damage degrades capability
B	Damage repair is required
C	Acceptable damage, no repair required

Figure 5. Proposed ISS damage classes

Use of a general technical manual will allow the repair team to ensure a thorough assessment of the damage, and determine the most effective procedure for repair.

Another important operational issue applicable to ISS repair operations is human factors. The ABDR environment has evolved to include various threat levels for airmen conducting repair operations. As a worst case scenario, ABDR teams must be prepared to operate in a hostile environment where chemical or biological weapons may be used. Therefore, teams are prepared to repair aircraft while wearing full chemical gear, which includes an overgarment, helmet, chemical mask, hood, boot covers, and gloves with inserts (see Figure 6). Preparing for

Figure 6. Full chemical gear.

repair operations operations in chemical calls many human issues into focus. Lengthened repair time, fatigue, work-rest cycles, tool design, lighting and access to damage areas are just a few issues that ABDR teams have dealt with in order to improve efficiency of ABDR operations. Considering tool access as a top priority, a mobile trailer containing essential repair tools, equipment and repair materials was developed to improve worker efficiency and reduce fatigue. Furthermore, a training program was developed for ABDR teams to practice repair scenarios while wearing full chemical gear. The training program allowed teams to build confidence in their ability to assess and repair aircraft damage.

Recognizing the existing challenges of on-orbit extravehicular activities (EVA), extensive testing and training is recommended in order to prepare for ISS repair operations. Once repair procedures are defined and mature, recurrent training should be conducted in order for repair teams to become accustomed to applying repair strategy. The majority of training can be conducted in the underwater Neutral Buoyancy Laboratory (Figure 7). Repair team members

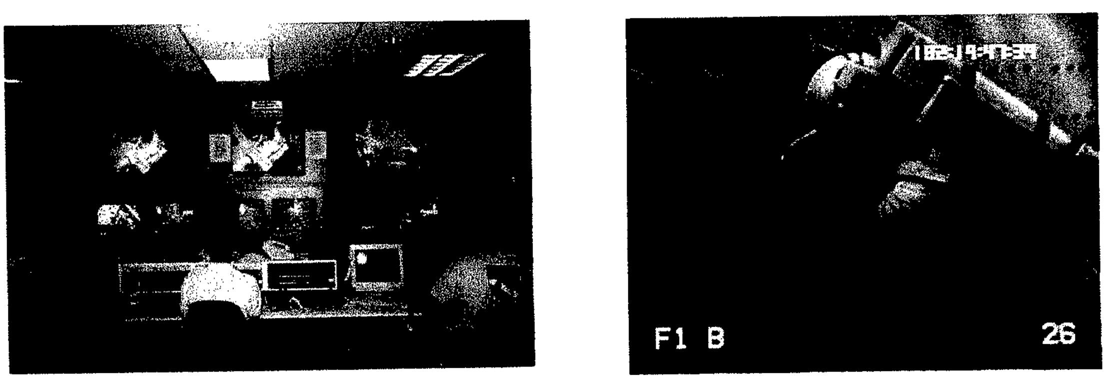


Figure 7. Initial NBL tests of ISS temporary damage repair operations.

should be provided an operational scenario requiring assessment and repair of a given damage. The damage should be real, and created using a hypervelocity impact gun. The goal of the team should be to assess the damage, develop a strategy, and repair it within a given time limit. Using this training method, critical operational issues such as access, lighting, damage assessment, crew workload, tool usage, and repair instructions can be assessed. Final training evaluations can be conducted onboard the Space Shuttle or ISS as a Detailed Test Objective (DTO).

Given the lessons learned from ABDR, pre-planning for repair operations onboard the ISS is a must. Thorough procedural classification of structures and damages, coupled with operational training for repair teams will maximize preparation and allow the conduct of efficient repair operations onboard the ISS (Figure 8).

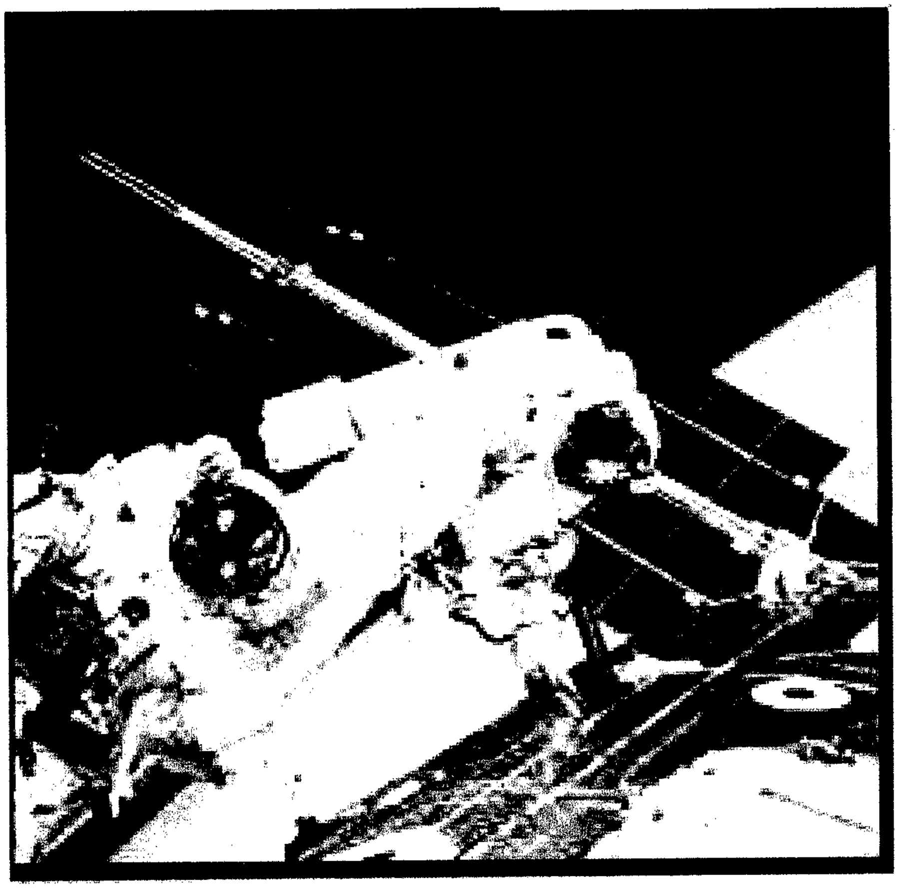
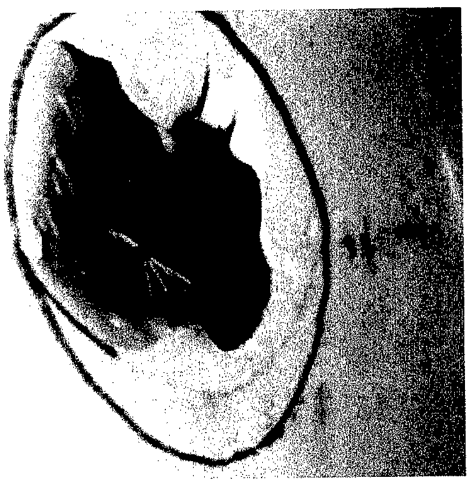


Figure 8. Depiction of potential ISS damage assessment activities

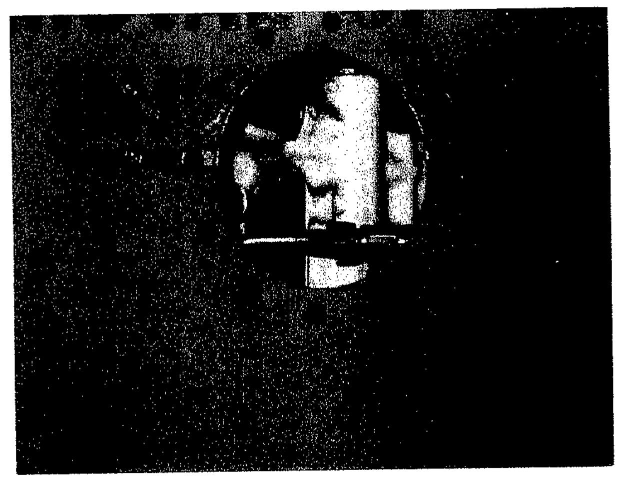
Technical Lessons Applicable to ISS Repair

At the technical level, damage preparation, analysis based upon material allowables, damage to critical systems and specialized damage effects have shaped ABDR techniques, and are applicable to repair operations onboard the ISS.

Prior to actual repair activities, the damage must be freed of foreign particles, jagged edges, and stress cracks. This task, known as damage "clean-up," removes foreign particles from the damaged surface and blends out cracks where stress concentrations may occur. Once the damage is cleaned-up, the repair team can design a repair based upon the final measurements of the cleaned-up damage. Figure 9 depicts an F-15 damage prior to, and after clean-up. Although this activity may be difficult to accomplish in the on-orbit environment, damage clean-up prevents crack propagation and reduces the probability of "zipper effect," or catastrophic propagation of cracks under load.



Before Damage Clean-up



After Damage Clean-up

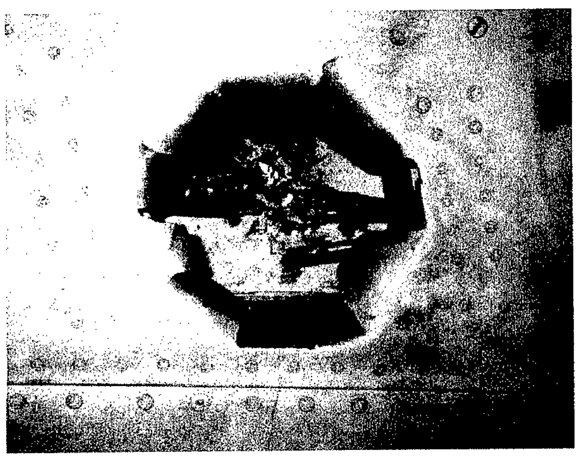
Figure 9. F-15 Damage before and after clean-up.

Once clean-up operations are complete, a repair strategy based upon material allowables is recommended. Details of structural analysis and repair are not provided in this paper, since specific techniques may prove to be infeasible for on-orbit repair operations. The general repair strategy stems from a simple analysis of the load carrying ability lost due to the damage area, followed by the design of a repair based upon material allowables. This approach is pre-determined for individual structures on each aircraft, and is provided in T.O.s. Repair materials, patches, and fasteners are recommended based upon primary loading for a given structure (i.e. shear, tension, bending, compression, pressure, etc.). For damages that exceed T.O. specifications, engineers design new repairs, and determine margins of safety for each repair. This strategy can also be employed on ISS repairs. In essence, repair designs are similar for every damage. To a certain degree, variations are expected depending on the exact nature of the damage. For repair of ISS structures the following steps are recommended:

1. Evaluate the damage and determine the probable loading scenario (i.e. tension, compression, shear, pressure, bending, etc.
2. Identify the damaged material and determine material allowables using MIL-HDBK-5H or other aerospace material properties documents.
3. Calculate the load lost through analysis of the damage area.
4. Determine repair design (material required, number of fasteners, etc.) and compare it's load bearing capability to the original allowables.

5. Verify repair margins of safety based upon the comparison of allowables.
6. Fabricate and test/install repair.

Another technical issue that has evolved in ABDR is the rapid repair of critical aircraft systems. Damage to avionics, high-pressure utility lines and hydraulic pressure vessels have caused repair teams to develop standard methods for repairing these systems. Given the probability of hypervelocity impacts on the ISS, the capability to restore critical systems should be considered. Added to this, many umbilicals and pressure vessels on the ISS are located externally to ISS modules, making them extremely vulnerable to hypervelocity impacts (Figure 2). Figure 10 depicts damage to F-15 electrical, hydraulic, and fuel systems. Electrical and



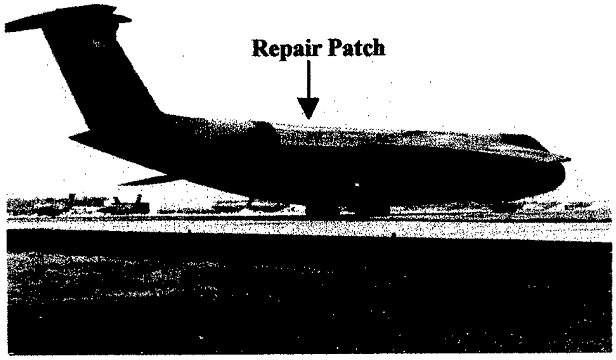
Substructure Electrical Damage

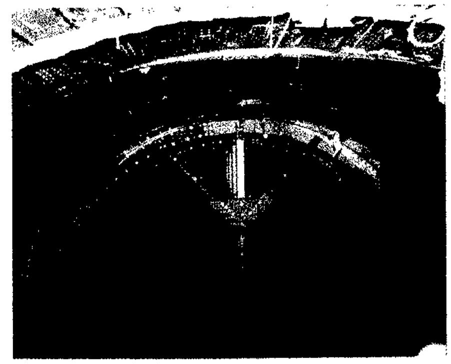
Fuel and Hydraulic System Damage

Figure 10. F-15 System Damage

hydraulic repair equipment (standard splicing tools, hydraulic interconnections, etc.) should be kept onboard the ISS should the need for restoration of critical systems arise.

The threat to critical systems also brings about the probability for specialized damage effects. Specialized damage effects are those damages that have a compounded effect on the system, usually resulting in some sort of catastrophic failure. Specialized damage effects in electrical systems can result in total electrical system failure, and can be caused by an impact to a small wire bundle. In liquid systems and pressure vessels, hypervelocity impacts can cause shock waves and a dynamic response, leading to a total explosion of the pressure vessel. The effects of heat and fire damage can be equally catastrophic. Entire structures can be rendered useless when subjected to heat and fire. Figure 11 depicts the repair of a C-5 due to ignition of a hydraulic leak in the aft troop cabin. The unique repair employed an outer aluminum patch strengthened with inner substructure consisting of wood and steel beams fastened by steel bolts. This temporary repair allowed a one-time ferry flight to Lockheed-Martin, where permanent repairs could be accomplished.





C-5 External Repair of Fire Damage　　　　Internal Repair

Figure 11. Repair of C-5 caused by internal fire damage.

SUMMARY

The intent of this paper was to propose ABDR as a baseline for ISS repair activities at the operational and technical level. Research of USAF repair strategies at the technical and operational level should be utilized to the maximum extent possible in order capitalize existing aerospace repair techniques. The reader is encouraged to further examine lessons learned from the assessment, analysis, and repair of aircraft damage, in order to develop a robust strategy for the repair of the ISS modules and systems.

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D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

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